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Theeuwes, J.; van der Burg, E.

### **published in**

Journal of Experimental Psychology: Human Perception and Performance  
2007

### **DOI (link to publisher)**

[10.1037/0096-1523.33.6.1335](https://doi.org/10.1037/0096-1523.33.6.1335)

### **document version**

Publisher's PDF, also known as Version of record

### [Link to publication in VU Research Portal](#)

### **citation for published version (APA)**

Theeuwes, J., & van der Burg, E. (2007). The role of spatial and non-spatial information in visual selection. *Journal of Experimental Psychology: Human Perception and Performance*, 33(6), 1335-1351.  
<https://doi.org/10.1037/0096-1523.33.6.1335>

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# The Role of Spatial and Nonspatial Information in Visual Selection

Jan Theeuwes and Erik Van der Burg  
Vrije Universiteit

Even though it is undisputed that prior information regarding the location of a target affects visual selection, the issue of whether information regarding nonspatial features, such as color and shape, has similar effects has been a matter of debate since the early 1980s. In the study described in this article, measures derived from signal detection theory were used to show that perceptual sensitivity is affected by a top-down set for spatial information but not by a top-down set for nonspatial information. This indicates that knowing where the target singleton is affects perceptual selectivity but that knowing what it is does not help selectivity. Furthermore, perceptual sensitivity can be enhanced by nonspatial features, but only through a process related to bottom-up priming. These findings have important implications for models of visual selection.

**Keywords:** selective attention, nonspatial selection, bottom-up priming, location cueing

As a metaphor, visual attention has been compared to a spotlight that selects parts of the visual world around us (e.g., Posner, 1980). Visual attention allows people to select information that is relevant for their ongoing behavior. For several decades, there has been agreement that there are two functionally independent stages of visual processing (e.g., Broadbent, 1958; Neisser, 1967; Treisman & Gelade, 1980). An early visual stage, sometimes referred to as preattentive, operates in parallel across the visual field; and a later stage, often referred to as attentive, can deal with only one or a few items at the same time. Even though the dichotomy between these two stages appears not to be as strict as originally assumed, this basic architecture is more or less still present in almost all past and present theories of visual attention (e.g., Itti & Koch, 2001; Li, 2002; Treue, 2003; Wolfe, 1994). Given the two-stage framework, it is generally assumed that visual selection depends principally on the outcome of the early stage of visual processing. Processing occurring during the initial wave of stimulation through the brain determines which element is selected and passed on to the second stage of processing. In line with the two-stage approach, passing on an item to the second stage of processing implies that this item has been selected for further processing (e.g., Broadbent, 1958; Treisman & Gelade, 1980).

Since the late 1970s and early 1980s, there has been agreement that visual selective attention can be directed to a nonfixated location in space (e.g., Eriksen & Hoffman, 1973; Hoffman, 1975; Posner, Snyder, & Davidson, 1980). Providing information about the location of an upcoming target may enhance the efficiency of processing (e.g., Posner et al., 1980), reduce stimulus uncertainty (e.g., Eckstein, Shimozaki, & Abbey, 2002; Palmer, 1994), reduce

interference from unattended locations (e.g., Theeuwes, 1991), or suppress masking at attended locations (Enns & Di Lollo, 1997). The effective utilization of spatial information is related to the attention mechanism that operates analogous to a beam of light. As a metaphor, Posner described visual selective attention as a “spotlight that enhances the efficiency of the detection of events within its beam” (Posner, 1980, p. 172).

Providing information about the location of an upcoming target usually involves a cueing procedure in which a cue indicates with a high probability (e.g., in 80% of the trials, the information provided to the participant is valid) the location of the upcoming target. Such a cue may consist of a centrally presented arrow that points to the likely target location (e.g., Posner, 1980), or a word (such as *right* or *left*; e.g., Vecera & Rizzo, 2004) indicating with a high probability the likely target location. Cueing in this way is typically referred to as endogenous or top-down, because participants are instructed to use this information in a top-down way to improve their performance.

In the so-called exogenous version of the location cueing paradigm, the cue has no predictive value regarding the location of the upcoming target (e.g., Jonides, 1981). Typically, before the appearance of the target, an uninformative peripheral event (usually an abrupt increase in luminance) is presented either at the location of the target or at a location where the target does not appear. The important finding is that, when the cue happens to be valid (i.e., the target happens to appear in the cued location), response times are fast and accuracy is high compared to a condition in which the cue is invalid (i.e., the target appears in the uncued location). The finding that a cue that has no predictive value regarding the upcoming target can induce spatial cueing effects is considered to be evidence that exogenous cueing is bottom-up and automatic (Jonides, 1981; LaBerge, 1981; Yantis & Jonides, 1990).

Even though there is agreement regarding the effect of location information on visual selective attention, there is less agreement on whether nonspatial information can also affect the efficiency of selection (e.g., Duncan, 1981; Kim & Cave, 1995; Lambert & Hockey, 1986; Theeuwes, 1989). In a recent review, Lamy and Tsal (2001) noted that in the last 3 decades the question whether

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Jan Theeuwes and Erik Van der Burg, Department of Cognitive Psychology, Vrije Universiteit, Amsterdam, Netherlands.

This research was funded by Human Frontier Science Program Grant HSFP-RGP39/2005 to Jan Theeuwes.

Correspondence concerning this article should be addressed to Jan Theeuwes, Department of Cognitive Psychology, Vrije Universiteit, van der Boechorststraat 1, 1081 BT Amsterdam, The Netherlands. E-mail: J.Theeuwes@psy.vu.nl

nonspatial attention can affect selection has been repeatedly posed. This question is posed not without reason because the extent to which nonspatial information can affect visual selection is fundamental and has major implications for theories of visual selective attention.

In the early 1980s, Posner et al. (1980) addressed this very same question. They showed that information about the location of the upcoming target improved the detection of signals. By *detection* Posner et al. meant "the entry of information concerning the presence of a signal into a system that allows the subject to report the existence of the signal by an arbitrary response" (p. 162). The question then posed was whether "the entry of information concerning the presence of a signal into a system" can also be improved by any information about the target that serves to disentangle the signal from noise (see also, Lappin & Uttal, 1976). Posner et al. concluded that the detection of signals can only be improved by information about its location and not by other information, such as its color.

Since the seminal paper of Posner et al. (1980), the question whether all features are equal or whether location has a special status in separating signal from noise has been a matter of debate. According to theories that claim that all features are equal, in order to select information, a target template (representing its location, its shape, or its color) has to be matched to the stimulus representation. Weights are assigned proportionally to the degree of the match (e.g., Bundesen, 1990; Duncan & Humphreys, 1989): the higher the weight, the higher the probability that the stimulus is selected for further processing. Weights can be set on the basis of any criterion, be it color, shape, movement, location, etc. Even though it is undisputed that location information improves the detection of signals (e.g., Cave & Pashler, 1995; Kim & Cave, 2001; Lamy & Tsal, 2001; LaBerge, 1981; Posner et al., 1980; Tsal & Lamy, 2000), it is still unclear whether information about nonspatial features has a similar effect. Whereas some studies have provided evidence that prior knowledge regarding nonspatial features had no effect on visual selection (e.g., Cave & Pashler, 1995; Posner et al., 1980; Kim & Cave, 2001; Tsal & Lavie, 1988; Theeuwes, 1989), other studies provided evidence that nonspatial features may improve the entry of information into the brain (e.g., Brawn & Snowden, 1999; Humphreys, 1981; Lambert & Corban, 1992; Laarni, 1999; Lappin & Uttal 1976; Vierck & Miller, 2005).

Findings obtained with the partial report paradigm (Sperling, 1960) seem to suggest that selection on the basis of nonspatial features is highly efficient. For example, von Wright (1970) showed efficient selection in a partial report task on the basis of simple attributes, such as color, luminance, and shape (see also, e.g., Brouwer & van der Heijden, 1996; Bundesen, Pedersen, & Larsen, 1984). These findings may suggest that nonspatial features can be used to select information. However, as pointed out by van der Heijden (1993), these findings do not indicate that nonspatial information is directly used to select information (as, for example, assumed by Bundesen's theory of visual attention, 1990). As shown by van der Heijden (1993), the nonspatial information points to a location in the display (similar to a bar-marker indicating a location); and, ultimately, location is used as a means to select the relevant item (see also, Tsal & Lavie, 1988).

Shih and Sperling (1996) came to a similar conclusion. They used a rapid visual serial presentation paradigm consisting of superimposed stimulus arrays. They showed that participants were

better at detecting a target digit when it was the color (or size) they expected but only when the target was in a frame with distractors having all different colors. Obviously, in this condition, the expected nonspatial feature provided spatial information about the target. In conditions in which the elements in a single frame had the same color and the expected nonspatial feature provided temporal but not spatial information, participants could not use this information to improve performance. Similar to van der Heijden (1993), Shih and Sperling (1996) concluded that nonspatial information does not directly affect visual selection but only guides spatial attention to the relevant location.

Along similar lines, Moore and Egeth (1998) concluded that direct selection on the basis of a nonspatial feature, such as color, was not effective. In their experiments, participants had to detect a digit among letters. Targets and distractors were either green or blue, although participants were informed regarding the probability of the target being in one of these colors. The higher the probability of a specific color, the faster the responses to targets in that specific color, indicating that selection by color was effective. However, in subsequent experiments, the display was presented briefly and masked, rendering color cueing ineffective. Moore and Egeth argued that masking the brief display prevented a shift of spatial attention to the relevant color. Therefore, they concluded, color cannot affect selection directly but only by guiding attention to the relevant location.

In a recent study, Vierck and Miller (2005) suggested that one can select on the basis of color. They used a rapid serial visual presentation task in which 15 different colored letters were presented. At the beginning of each trial, the color of the target letter was cued; and the cue was valid, neutral, or invalid. Even though color information was not necessary for the task, valid cues resulted in better performance and invalid cues in worst performance relative to the neutral condition. Even though, on the face of it, this study appears to provide evidence for visual selection on the basis of color, recent evidence shows that color cueing in such Rapid Serial Visual Presentation experiments may have to do with uncertainty reduction rather than visual selection (see Vierck & Miller, 2007).

The question that needs to be addressed is whether preknowledge regarding particular features of the upcoming target directly facilitates the selection of that target. To put it in terms of Posner et al. (1980, p. 162), the question is whether "the entry of information . . . into the system" is modulated by nonspatial information. Several modern theories of visual attention implicitly or explicitly assume that selection on the basis of location is in principle not different than selection on the basis of other stimulus properties, such as color, shape, etc. (see, e.g., Bundesen, 1990; Cave & Bichot, 1999; Kahneman, 1973; Wolfe, 1994). For example, in Bundesen's theory of visual attention (1990), selection can take place by color, form, or position because the observer may adjust so-called "pertinence values," which are considered to be (top-down) weights that represent the importance of attending to objects that belong to a particular category.

From a neurophysiological point of view, we pose the question whether top-down expectancies can modulate neural activity by enhancing the responses of neurons tuned to a feature that may either be spatial or nonspatial. For example, recently Carrasco, Ling, and Read (2004) showed that location cueing alters the apparent stimulus contrast. These results imply that directing spa-

tial attention results in a greater neuronal sensitivity (i.e., a decreased threshold), changing the strength of the stimulus by increasing its salience. Along similar lines, we address the question whether top-down knowledge of nonspatial properties of the target can alter the salience of that target. For example, when we know that the upcoming target is red, is the salience of all red items in the display enhanced?

To determine whether top-down knowledge can affect the initial selection of stimuli, we used a feature singleton search task. In this task, the target is unique in a basic feature dimension (e.g., a red element surrounded by green elements) and therefore pops out from the display. The question is whether top-down knowledge modulates the salience of the popping-out target. In terms of neurophysiology, the question is whether neurons in early vision (e.g., primary visual cortex) can be tuned in a top-down way to specific local features, such as location, color, and shape. Using a feature singleton task enabled us to investigate top-down modulation on early (feedforward) vision, thereby excluding later top-down modulations arising from massive recurrent processing from extrastriate areas to primary visual areas. Indeed, pop-out detection tasks have been implicated to subserve the first stage of visual processing and single unit studies have implicated primary visual cortex in mediating bottom-up pop-out saliency computations (e.g., Nothdurft, Gallant, & Van Essen, 1999).

With respect to spatial information, Theeuwes, Kramer, and Atchley (1999) showed that even in a pop-out search task, location cueing is effective. When an exogenous cue (an abrupt onset) cued the approximate area where a color singleton could appear, detection times were faster than when it cued the invalid location where the color singleton did not appear. Even though it was a singleton, location information provided benefits in detecting the pop-out target element (see also Theeuwes, Kramer, & Atchley, 2001).

There is also evidence that nonspatial information affects feature singleton search. Whereas knowing the actual feature value of the target (whether it is blue, red, or white between green nontargets) hardly speeded search, Treisman (1988) showed that knowing the dimension of the target (whether it would be a unique color or a unique shape) speeded search by about 100 ms (i.e., it reduced the search intercept by about 100 ms). Similar results were obtained in a recent study by Müller, Reimann, and Krummenacher (2003). In this study, the likely dimension of the target singleton was cued in advance. Observers searched for a target singleton that had a unique color (color singleton) or a unique shape (shape singleton). Before each trial, the likely target dimension was cued in advance. For example, the word *color* was presented before a trial to indicate that it was likely (80%) that the upcoming target would be a color singleton. Similarly, when the word *shape* was presented, there was an 80% chance that a shape singleton would be presented. Müller et al. (2003) showed a clear validity effect, that is, when the verbal cue indicated the correct dimension of the upcoming target singleton (either color or shape) observers were fast; if expectations were incorrect, participants were slow. The typical explanation for these findings is that top-down modulation allows a faster and more efficient selection of the target (e.g., Müller et al., 2003; Treisman, 1988; Wolfe, 1994; Wolfe, Butcher, Lee, & Hyle, 2003). For example, according to the dimensional weighting account of Müller et al. (2003; see also Wolfe et al., 2003), knowing the dimension in advance allows attentional weight to be assigned to the relevant (known, pre-cued) dimension.

According to Müller et al., assigning weights according to the known likelihood of a target appearing in a particular dimension permits a rapid search. Note that, according to these theories, top-down knowledge guides the search process. That is, top-down knowledge affects the selection process of the featural singleton. Even though these findings seem to imply that cueing nonspatial features can help the selection process, others have claimed that these effects are the result of factors related to the selection of a response (Cohen & Magen, 1999; Cohen & Shoup, 1997; Mortier, Theeuwes, & Starreveld, 2005).

Another influential theory that claims that top-down knowledge guides the search process is the contingent-capture theory of Folk and colleagues (Folk, Remington, & Johnston, 1992; Folk & Remington, 1998). According to this notion, only stimuli that match the top-down control settings are selected for further processing, whereas stimuli that do not match the top-down settings are ignored. Even though the contingent-capture hypothesis was mainly tested with experiments investigating the extent to which irrelevant distractors can capture attention, the basic claim of this theory is that top-down set including spatial and nonspatial information has a determining effect on the efficiency of visual selection.

The present study was designed to determine whether cueing nonspatial features can affect visual selection. We wanted to determine whether directing nonspatial attention can enhance visual processing. In other words, can a top-down set for a nonspatial target feature enhance the signal-to-noise ratio (e.g., Lu & Doshier, 1998)? As noted in a recent paper by Prinzmetal, McCool, and Park (2005), in order to determine whether cueing affects the perceptual representation—which Prinzmetal et al. refer to as channel enhancement—one should design experiments around accuracy with briefly presented displays. Prinzmetal et al. (2005) showed that reaction time (RT) differences do not necessarily reflect differences in channel enhancement because RT differences can be the result of differences in decision processes. Therefore, instead of measuring response latency, we employed methods derived from signal detection theory (SDT) in briefly presented displays. We calculated  $A'$  (and related measures, such as  $d'$ ) to determine whether preknowledge regarding the upcoming target would modulate target detectability. In other words, by calculating  $A'$ , we could determine the extent to which spatial and nonspatial information would modulate the entry of information concerning the presence of a signal into a system.

To determine whether preknowledge of information affects the sensory gain of inputs, measures derived from SDT have advantages over traditional reaction-time measures. Preknowledge of information (i.e., cueing) may either facilitate processing in sensory pathways that code input from the visual field (e.g., Hawkins et al., 1990; Handy, Jha, & Mangun, 1999) or may affect decision making processes (e.g., response biases) occurring at later stages of processing (e.g., Shaw & Shaw, 1977; Duncan, 1981). As argued by McDonald, Teder-Sälejärvi, and Hillyard (2000), “unlike reaction times, signal detection measures allow for a separation of perceptual and decision-level effects of attention” (p. 906). If spatial and nonspatial attention modulates the efficacy of sensory processing by increasing the sensory gain for particular inputs (e.g., gains for a particular color, location, or shape), one would expect an effect on sensitivity. Measures from SDT, such as  $A'$  and  $d'$ , typically reflect early perceptual processing, such as the sen-

sory encoding of a stimulus (Handy, Kingstone, & Mangun, 1996; McDonald et al., 2000). Alternatively, if cueing affects processing at later stages, one expects no change in perceptual sensitivity. Note that traditional reaction-time measures reflect both earlier, perceptual, and later, response-related operations (see, e.g., Handy et al., 1996; Prinzmetal et al., 2005).

To determine whether cueing affects visual selection, we employed a method similar to the one used in previous studies (Theeuwes, Kramer, & Kingstone, 2004; Theeuwes & Chen, 2005; see also Downing, 1988; Handy et al., 1999; Hawkins et al., 1990) that is basically derived from signal detection theory. Previous studies employing this method have demonstrated that location cueing can enhance gains for inputs presented at that location (e.g., Hawkins et al., 1990; Handy et al., 1999) and that attentional capture also results in an increased sensitivity at the location at which the singleton captured attention (Theeuwes & Chen, 2005).

### Experiment 1

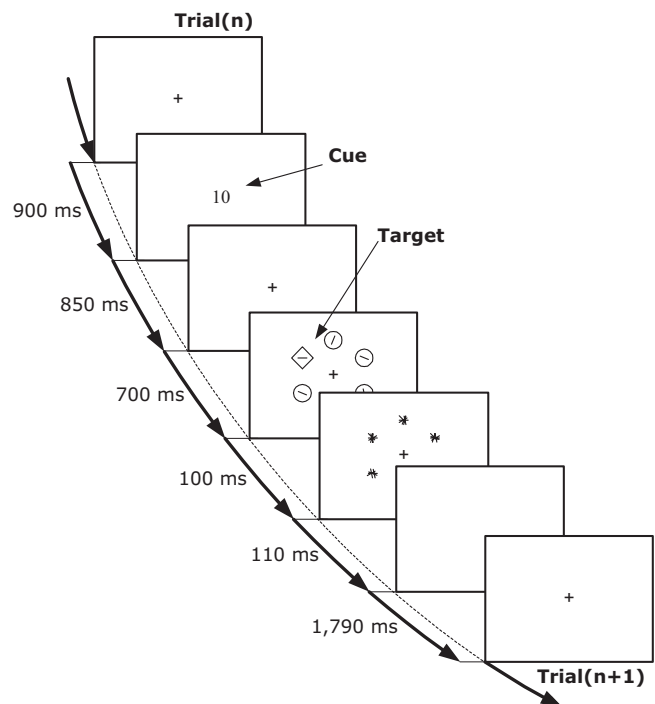
Before determining whether top-down knowledge of nonspatial features can affect visual selection processes, we first determined whether preknowledge of spatial information can affect visual selection. Unlike earlier studies that used a central arrow to direct attention (e.g., Posner, 1980), we used a truly endogenous location cue in which the likely target position was indicated by a number corresponding to the hour indication of an analogue clock (e.g., 12 is the top location, 2 is the top-right location, etc.; see also Downing & Pinker, 1985). Also, unlike earlier studies that used SOAs of 300 to 600 ms (the typical SOAs for endogenous cueing; see, e.g., Posner et al., 1980) we used an SOA of 1.55 s to allow observers to endogenously prepare for the upcoming target singleton. We monitored eye movements to make sure that observers remained fixated at the fixation point.

### Method

**Participants.** Ten students (8 women and 2 men; mean age = 25.0 years, ranging from 20 to 34 years) participated in the experiment as paid volunteers. All participants were naïve as to the purpose of the experiment.

**Apparatus.** A Dell computer with a 17-inch SVGA color monitor using E-prime controlled the timing of the events, generated stimuli, and recorded responses. Electro-oculograms (EOGs) were used to determine eye position. Horizontal and vertical EOGs were measured and recorded from tin electrodes attached to the outer canthi of each eye and above and below the right eye. The left cheek was used as ground reference. EOG recordings were amplified, low-pass filtered (0-100 Hz), digitized (1000 Hz), and processed by NeuroScan (Sterling, VA) hardware and software.

**Stimuli.** Figure 1 shows an example of an experimental trial. A trial started with a presentation of a light gray fixation cross,  $0.35^\circ$  height and  $0.35^\circ$  width, luminance  $29.3 \text{ cd/m}^2$ , at the middle of the screen for a fixed period of 900 ms. The luminance of the dark gray background was kept constant at about  $0.56 \text{ cd/m}^2$ . Immediately after the presentation of the fixation-cross, a light gray location cue was presented for a period of 850 ms at the center of the screen; it indicated the location of a target singleton with a validity of 80%. The characters of the location cue were presented in 18-point Courier New font ( $0.46^\circ$  width and  $0.43^\circ$  height) and



**Figure 1.** Outline of the used paradigm and the layout of the search display in the Experiment 1. Participants received a fixation-cross immediately followed by a location cue, which informed participants about the location of the target singleton in the search display which informed participants about the location of the upcoming target singleton with a validity of 80%. In this example, the location cue is 10, which indicated the target singleton was probably placed at 10 o'clock in relation to the fixation cross. After the presentation of the location cue, another fixation cross was placed. This was directly followed by the search display. Participants made an unspeeded response or withheld their response depending on whether the line segment in the target singleton was horizontally or vertically oriented.

consisted of the numbers 2, 4, 6, 8, 10, and 12. Each number represented a position on an analogue clock and, therefore, information about the target location. For example, a location cue showing the number "12" represented the 12 o'clock position on a clock face, i.e., the position straight above the fixation point.

After the cue was presented, the fixation cross reappeared for a fixed period of 700 ms, followed by a search display with six items equally spaced around the fixation cross on an imaginary circle with a radius of  $5.3^\circ$  for a period of 100 ms. During the practice block the display duration was 140 ms. The display consisted of five identical green distractor circles and one target singleton, which either had a different color (color singleton condition) or a different shape (shape singleton condition). The distractor circles were green outline circles with a luminance of  $11.6 \text{ cd/m}^2$  and a radius of  $1.1^\circ$ . The color singleton was identical except that its color was red (luminance of  $13.5 \text{ cd/m}^2$ ). The shape singleton was an outline diamond (each side was  $2.0^\circ$ ) with the same green outline color as the green distractor circles. Inside each display element, a grey line segment was placed (luminance  $29.3 \text{ cd/m}^2$ ). In the distractor circles, the line segments were tilted  $22.5^\circ$  to either side of the horizontal or vertical plane (see Theeuwes et al.,



2004; Theeuwes & Chen, 2005). In the singleton, the target line segment (initially set at a length of  $1.1^\circ$ ) had either a vertical or a horizontal orientation. Note that a vertical or horizontal line segment does not pop out among slightly tilted line segments (see Theeuwes, 1991), which makes it impossible that participants searched directly for the target line segment instead for the shape singleton (the diamond) that contained the target line segment. The mask consisted of 30 randomly filled gray line segments that appeared over the line segments. All the line segments and the masks were equiluminant at  $29.3 \text{ cd/m}^2$ .

**Procedure.** Participants responded to the target line segment, either horizontal or vertical, which was always located in the singleton. Participants were required to direct their attention to the singleton and make a discrimination judgment of the target bar's orientation (i.e., vertical or horizontal) inside the shape singleton. Participants were required only to respond with the space bar to one of the designated orientation (horizontal or vertical). Orientation was counterbalanced across participants. A hit was defined as a response on trials in which the designated target orientation was present, and a false alarm was defined as a response on trials in which the designated target orientation was absent. Accuracy was stressed. When participants committed an error (miss or false alarm) a tone sounded. Participants were instructed to remain fixated on the central fixation point during the course of a trial.

In the experiment, we used the exact same adjustment procedure as in Theeuwes et al., (2004) and Theeuwes and Chen (2005). In order to minimize the possibility of floor or ceiling effects in accuracy, target line length was adjusted online to ensure that that performance remained near 75% correct. Every 10 trials, the overall performance (hits and false alarms) was calculated. If the accuracy dropped below 65%, line length was increased  $0.08^\circ$ . If performance was better than 85% line length was reduced  $0.08^\circ$ . This adjustment was done on the basis of the preceding 10 trials.

**Experimental design.** The independent variables were target singleton (color or shape) and cue validity (valid or invalid). The 6 target positions out of 12 possible positions were randomly determined during the experiment. On each trial, there was an equal probability of a color singleton or a shape singleton. The orientation of the line segment in the target singleton, horizontal or vertical, was randomized. The presentation of a valid or an invalid location cue was also randomized, with the constraint that the probability of a valid location cue was 80% and an invalid location cue was 20%. In case the cue was invalid, the target singleton was presented at the location opposite the cued location. Each participant performed 120 practice and 600 experimental trials. In 480 trials, the cue was valid. In 120 trials, it was invalid. In half of the trials, the display contained a color singleton; the other half contained a shape singleton. Target position was balanced. All conditions were randomized within blocks.

## Results

Trials in which eye movements were made were excluded from the analysis. This led to a loss of 2.1% of the trials. The mean percentage hits and false alarms for each condition were used to calculate  $A'$ <sup>1</sup>. Table 1 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  as a function of target singleton and cue validity. We conducted an analysis of variance (ANOVA) on  $A'$  with target singleton and cue validity as factors. There was

Table 1

*Results of Experiment 1 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean  $A'$  as a Function of Target Singleton and Cue Validity*

| Variable         | Color target singleton |             | Shape target singleton |             |
|------------------|------------------------|-------------|------------------------|-------------|
|                  | Invalid cue            | Valid cue   | Invalid cue            | Valid cue   |
| Hits (%)         | 75.8 (16.5)            | 92.0 (6.1)  | 61.4 (24.5)            | 86.6 (6.6)  |
| False Alarms (%) | 34.9 (12.1)            | 24.4 (4.8)  | 33.3 (15.7)            | 20.6 (6.0)  |
| $A'$             | 0.78 (0.13)            | 0.91 (0.01) | 0.71 (0.13)            | 0.90 (0.02) |

*Note.* Standard deviations are shown in parentheses.

a marginally significant effect of target singleton,  $F(1, 9) = 4.656$ , mean square error ( $MSE$ ) = .003,  $p = .059$ , suggesting better performance with color singletons than with shape singletons. More importantly, there was a highly significant main effect of cue validity,  $F(1, 9) = 20.268$ ,  $MSE = .012$ ,  $p = .001$ , indicating that participants performed better when the cue was valid (.90) than when it was invalid (.75). There was no interaction between target singleton and cue validity ( $F = 1.642$ ).

## Discussion

The present results are clear. Advance information about the location of an upcoming target singleton improves target detectability ( $A'$ ). In line with earlier studies (e.g., Hawkins et al., 1990; Handy et al., 1999), Experiment 1 shows that spatial cueing enhances gains for inputs at the cued location. Unlike previous studies that typically have used a central arrow presented 300 to 600 ms before the onset of the stimulus display (e.g., Hawkins et al., 1990), we used a genuine endogenous cue, a number that had to be interpreted, presented 1.55 s prior the stimulus display onset. It is known that central arrows may not direct attention in a genuinely top-down way to a location in space as initially assumed. For example, Hommel, Pratt, Colzato, & Godijn (2001) have shown that nonpredictive symbolic cues (e.g., arrows) may direct attention in an exogenous way. Because our cue was a number representing the locations on a clock face, we ensured that attention was directed to the cued location in a genuine top-down way. Note that the location cueing benefits cannot be attributed to eye shifts in the direction of the cued location because we measured eye movements and trials in which eye movements were made were excluded from the analysis.

It is important to note that the current experiment shows that advance location information can improve the target detectability even when the target is a pop-out singleton. Even though it is assumed that singletons are detected preattentively, that is, without

<sup>1</sup> Because in some conditions for some participants, the hit or false alarm rates approached 100% or 0%, respectively, we quantified sensitivity with nonparametric measures of  $A'$ .  $A'$ -prime is a nonparametric analogue of the  $d'$ -prime statistics (Snodgrass & Corwin, 1988). An  $A'$ -prime score of .5 indicates that the participants did not discriminate at all and a score of 1 indicates when performance is perfect. For completeness and because of the overall familiarity of the  $d'$  measure, we provide  $d'$ s for all experiments in Appendix A.

the need for attention (e.g., Treisman & Gelade, 1980), the current experiment shows that directing attention to the likely target position still has a very large effect on target detectability. These findings are consistent with those of Theeuwes et al., (1999) who showed similar effect on target detection time with an exogenous cue (an abrupt onset).

## Experiment 2

Experiment 1 established that preknowledge of the location of the upcoming target has a large effect on target detectability. In line with the numerous cueing studies that have been conducted since the 1970s and early 1980s, these findings confirm that spatial information can affect visual selection processes. The question that is central to the present study is whether other, nonspatial, cues can have a similar effect. In Experiment 2, we provided nonspatial information regarding the upcoming target singleton. Thus, for example, we used the word *color* as a cue, which indicated that 1.5 s later there was an 80% probability that the target singleton would be a color singleton. In 20% of the trials, the target singleton would be a shape singleton. In addition, if the word *shape* was presented as a cue, there was an 80% probability that the target singleton would be a shape singleton and a 20% probability that it would be a color singleton.

We cued the dimension of the upcoming target singleton because search studies using RT as the dependent measure showed that cueing the likely dimension of a target singleton affected target detection time (Müller et al., 2003; see also Theeuwes, Reimann, & Mortier, 2006). In addition, Treisman (1988) showed that knowing the actual feature value of the target (whether it is blue, red, or white between green nontargets) hardly speeded search, although knowing the dimension of the target (whether it would be a unique color or a unique shape) had a large effect on RT.

If the nonspatial cues help direct attention to the location of the target singleton, just as a location cue did in Experiment 1, we expected to find a cue validity effect on  $A'$ .

## Method

**Participants.** 10 students who had not participated in the previous experiment (8 men and 2 women; mean age = 22.0 years, ranging from 18 to 29 years) participated in the experiment as paid volunteers.

**Apparatus.** For this and all following experiments, the same equipment was used as in Experiment 1 except that we no longer measured eye movements.

**Design, stimuli, and procedure.** The experiment was exactly the same as Experiment 1 except that the cues indicated with 80% validity the dimension of the upcoming target. Thus if the Dutch word for shape, *vorm*, was presented, observers knew with an 80% probability that the shape singleton would be presented and with a 20% probability that the color singleton would be. Also, when the Dutch word for color, *kleur*, was presented, observers knew with an 80% probability that a color singleton would be presented and with a 20% probability that a shape singleton would be. Note that the color singleton was always a red circle and the shape singleton a green diamond. The nontarget elements were always green circles. Note that in this and in the remaining experiments we did

not monitor eye movements because the cue did not provide location information. Because the display was presented only 140 ms, participants were not able to make any eye movements towards the target.

## Results

The data were analyzed in the same way as in Experiment 1, with target singleton and cue validity as within-subjects factors. Table 2 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  as a function of target singleton and cue validity.

There was a significant main effect of target singleton,  $F(1, 9) = 5.372$ ,  $MSE = .003$ ,  $p < .05$ , indicating that participants performed better when the target singleton was a color singleton (.86) than when the target singleton was a shape singleton (.82). There was no significant main effect of cue validity ( $F = 2.094$ ) and no significant main effect of the interaction between target singleton and cue validity ( $F = 2.316$ ).

## Discussion

The present data are clear. There was no effect of cue validity on target detectability. In other words, knowing that the upcoming target singleton is a color singleton or shape singleton does not affect the sensitivity in detecting these singletons. These results are crucial because they indicate that nonspatial information cannot influence the visual selection process. Note that Experiment 1, in which spatial information was provided, showed a large, reliable cueing effect, whereas the very same procedure in which nonspatial information was provided showed basically no cueing effect. This pattern of results was confirmed by a between-experiments comparison between Experiment 1 and 2. There was a highly significant interaction between experiment and validity,  $F(1, 18) = 9.057$ ,  $MSE = .004$ ,  $p < .01$ . None of the other interactions were reliable.

The current findings, showing no cueing effect of nonspatial information, are inconsistent with those reported by Müller et al. (2003), who showed that preknowledge of the properties of a target singleton speeds up the detection of that singleton (see also Wolfe et al., 2003). More importantly, the results are inconsistent with various theories that claim that preknowledge of the properties of a target singleton can guide attention in a top-down way to the relevant location (e.g., Müller et al., 2003; Wolfe et al., 2003). Our

Table 2  
*Results of Experiment 2 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean  $A'$  as a Function of Target Singleton and Cue Validity*

| Variable         | Color target singleton |             | Shape target singleton |             |
|------------------|------------------------|-------------|------------------------|-------------|
|                  | Invalid cue            | Valid cue   | Invalid cue            | Valid cue   |
| Hits (%)         | 79.7 (8.4)             | 85.4 (5.7)  | 77.7 (14.7)            | 80.5 (13.6) |
| False Alarms (%) | 27.7 (17.8)            | 22.3 (6.8)  | 32.0 (18.9)            | 33.8 (15.3) |
| $A'$             | 0.83 (0.11)            | 0.89 (0.02) | 0.82 (0.08)            | 0.82 (0.06) |

*Note.* Standard deviations are shown in parentheses.

findings indicate that there may be no effect of nonspatial feature on top-down guidance of attention.

Even though the results of Experiment 2 are clear, one might argue that participants did not prepare well enough for the upcoming target singleton because the cue was not 100% valid. Indeed, location cueing studies have shown that one may need a 100% valid location cue in order to obtain optimal focusing of attention (Yantis & Jonides, 1990). To determine whether a 100% valid cue would generate enough top-down control to affect target selectivity, we ran an experiment in which the word cue indicated with a 100% validity the dimension of the upcoming singleton.

### Experiment 3

The experiment was identical to Experiment 2 except that the cue was 100% valid. We compared this to a neutral condition in which no information was provided about the dimension of the upcoming target singleton.

#### Method

**Participants.** Sixteen students who had not participated in the previous experiments (9 men and 7 women; mean age = 20.9 years, ranging from 17 to 30 years) participated in the experiment as paid volunteers. All participants were naïve as to the purpose of the experiment.

**Design, stimuli, and procedure.** The experiment was exactly the same as Experiment 2 except that the cue validity was either valid or neutral. In the valid condition, the cue (color or shape) indicated with 100% validity the dimension of the upcoming target in the search display. In the neutral condition, the Dutch word for neutral, *neutraal*, which was noninformative about the upcoming target in the search display, was presented. The presentation of a valid or a neutral cue was randomized within blocks. Each participant performed 48 practice trials and 240 experimental trials.

#### Results

The data were analyzed in the same way as in the previous experiments. Table 3 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  as a function of target singleton and cue validity.

There was significant main effect of target singleton,  $F(1, 15) = 42.527$ ,  $MSE = .006$ ,  $p < .001$ , indicating that participants performed better when the target singleton was a color singleton (.94)

Table 3  
Results of Experiment 3 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean  $A'$  as a Function of Target Singleton and Cue Validity

| Variable         | Color target singleton |             | Shape target singleton |             |
|------------------|------------------------|-------------|------------------------|-------------|
|                  | Neutral cue            | Valid cue   | Neutral cue            | Valid cue   |
| Hits (%)         | 89.8 (5.9)             | 93.1 (4.5)  | 76.6 (20.3)            | 74.8 (19.5) |
| False Alarms (%) | 16.3 (10.5)            | 13.0 (9.7)  | 32.3 (17.7)            | 28.1 (14.6) |
| $A'$             | 0.92 (0.03)            | 0.95 (0.02) | 0.80 (0.12)            | 0.82 (0.09) |

Note. Standard deviations are shown in parentheses.

than when the target singleton was a shape singleton (.81). There was no effect of cue validity (Neutral = .86, Valid = .88), nor was there an interaction between target singleton and cue validity.

#### Discussion

Experiment 3 confirmed the findings of Experiment 2. Again there was no effect of cue validity on target detectability. Obviously, even when the cue was 100% valid, participants could not use this information to improve perceptual selectivity. These findings confirm our claim that nonspatial information cannot influence the visual selection process.

Even though the current results suggest no guidance of attention by nonspatial information, one could argue that the verbal word cue indicating the dimension rather than the exact feature is not an adequate way to induce top-down guidance. Although it has been previously argued that, if anything, it is the dimension (such as the dimension color or shape) that induces expectancies rather than the exact feature values (such as red or diamond; see, e.g., Treisman, 1988; Müller et al., 2003), others have claimed that knowing the exact feature value may induce additional benefits (e.g., Wolfe et al., 2003; Meeter & Theeuwes, 2006). To test this notion in Experiment 4, instead of presenting a word that indicates the dimension, we presented a word that indicated the exact feature (*red* and *diamond* for the color and shape singleton conditions, respectively).

### Experiment 4

#### Method

**Participants.** Seventeen students who had not participated in the previous experiments (14 men and 3 women; mean age = 20.3 years, ranging from 17 to 35 years) participated in the experiment as paid volunteers. Data from two participants were excluded from the analysis because the mean percentage of hits plus the mean percentage of correct rejections was less than 60%. In addition, the data from one participant was excluded because the participant did not respond to the shape singleton (the mean percentage of hits and mean percentage of correct rejections for shape singleton trials was less than 60%).

**Design, stimuli, and procedure.** The experiment was exactly the same as Experiment 2 except that the cues indicated with an 80% validity the exact feature of the upcoming target singleton. Thus, when the Dutch word for diamond, *ruit*, was presented, observers knew with an 80% probability that the shape singleton would be presented and with a 20% probability that the color singleton would be. Also, when the Dutch word for red, *rood*, was presented, observers knew with an 80% probability that a color singleton would be presented and with a 20% probability that a shape singleton would be.

#### Results

The data were analyzed in the same way as in Experiment 2, with target singleton and cue validity as within-subjects factors. Table 4 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  as a function of target singleton and cue validity.



The analysis yielded a significant main effect of target singleton,  $F(1, 13) = 4.923$ ,  $MSE = .010$ ,  $p < .05$ , indicating that participants performed better when the target singleton was a color singleton (.86) than when the target singleton was a shape singleton (.80). More importantly, the main effect of cue validity failed to reach significance,  $F(1, 13) = 1.548$ ,  $MSE = .026$ ,  $p = .235$ . Furthermore the interaction between target singleton and cue validity was unreliable,  $F < 1$ .

### Discussion

Experiment 4 showed that even a word cue representing the exact feature value does not induce a cueing effect. The results corroborate the findings of Experiments 2 and 3 by showing that nonspatial information cannot affect the sensitivity in detecting singletons.

### Experiment 5

Experiments 2, 3, and 4 show that nonspatial information does not improve target detectability. Even though there was a reliable interaction between type of cue (color versus shape) and validity in none of these experiments (not even when the data of the three experiments were pooled<sup>2</sup>), at least numerically, it appears that color cueing may have had some effect. To test this explicitly, we focused solely on color cueing in Experiment 5. In this experiment, we used a verbal cue to indicate the color of the upcoming color singleton. For example, if *red* was presented as a cue, there was a high probability (75%) that the color singleton to search for would be a red singleton.

### Method

**Participants.** 10 students who had not participated in the previous experiments (6 women and 4 men; mean age = 19.5 years, ranging from 18 to 22 years) participated in the experiment as paid volunteers.

**Design, stimuli, and procedure.** The experiment was basically the same as Experiment 4 except that the word cues indicated with a 75% validity the exact color of the upcoming target singleton. The target singleton was always a color singleton among grey distractor circles (13.90 cd/m<sup>2</sup>). The color of the target singleton was randomly determined and was either red (13.55 cd/m<sup>2</sup>), green (13.90 cd/m<sup>2</sup>), blue (13.51 cd/m<sup>2</sup>), purple (13.03 cd/m<sup>2</sup>), or orange (13.36 cd/m<sup>2</sup>). For example, when the Dutch word for red, *rood*,

Table 4  
*Results of Experiment 4 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean A' as a Function of Target Singleton and Cue Validity*

| Variable         | Color target singleton |             | Shape target singleton |             |
|------------------|------------------------|-------------|------------------------|-------------|
|                  | Invalid cue            | Valid cue   | Invalid cue            | Valid cue   |
| Hits (%)         | 83.3 (11.4)            | 84.7 (7.0)  | 73.6 (22.9)            | 78.9 (9.1)  |
| False Alarms (%) | 31.1 (13.2)            | 19.7 (5.2)  | 29.4 (22.3)            | 26.6 (14.5) |
| A'               | 0.83 (0.09)            | 0.90 (0.03) | 0.78 (0.23)            | 0.82 (0.11) |

Note. Standard deviations are shown in parentheses.

Table 5

*Results of Experiment 5 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean A' as a Function of Target Singleton and Cue Validity*

| Variable         | Invalid cue | Valid cue   |
|------------------|-------------|-------------|
| Hits (%)         | 86.7 (5.2)  | 84.8 (5.1)  |
| False Alarms (%) | 19.4 (3.9)  | 21.7 (4.7)  |
| A'               | 0.90 (0.02) | 0.89 (0.01) |

Note. Standard deviations are shown in parentheses.

was presented, observers knew with a 75% probability that a red singleton would be presented. In 25% of the trials, a color singleton having a color other than red would be presented. Each participant performed one practice block (96 trials) and three experimental blocks (288 trials). All conditions were randomized within blocks.

### Results

Table 5 presents mean percentage hits, mean percentage false alarms, and mean A' as a function of cue validity. An ANOVA was conducted on the mean A' with cue validity as a factor. The analysis yielded no significant effect of cue validity, suggesting that participants were not able to use the information efficiently. If anything, participants performed worse when the cue was valid than when it was invalid ( $p = .09$ ).

### Discussion

The experiment showed that a word cue specifying the exact color participants have to search for has no effect on target detectability. These results are consistent with the findings from Experiments 2, 3, and 4, showing that nonspatial information cannot improve target detectability, not even when this information specifies the exact color of the upcoming target singleton.

### Experiment 6

The overall picture of Experiments 1 to 5 is clear: Spatial cueing (Experiment 1) has a large effect on detecting target singletons whereas nonspatial information (Experiments 2, 3, 4, and 5) does not improve target detectability. In Experiment 6, we manipulated spatial and nonspatial information simultaneously so as to directly compare the relative contributions of both spatial and nonspatial information on the detectability of target singletons.

### Method

**Participants.** Sixteen students who had not participated in the previous experiments (8 men and 8 women; mean age = 22.6

<sup>2</sup> We conducted a between-experiments ANOVA combining the data of Experiments 2, 3, and 4 to determine whether, with increased power, the factor cue validity would become reliable. We pooled the data of the valid conditions (Experiments 2, 3, 4) and those of the invalid (Experiments 2 and 4) and neutral (Experiment 3) conditions. With 40 participants, the effect of cue validity failed to reach significance,  $F(1, 37) = 4.068$ ;  $p = .051$ .

years, ranging from 18 to 35 years) participated in the experiment as paid volunteers.

**Design, stimuli, and procedure.** The experiment was basically the same as the previous experiments except that the cue contained both spatial and nonspatial information. The variables manipulated were nonspatial cue validity (valid or invalid) and spatial cue validity (valid or invalid) for both color and shape singletons. In each trial, a cue was presented consisting of the combination of a nonspatial word cue and a location word cue. In most trials, the nonspatial and spatial word were both valid (70%). In the remaining trials, either (a) the location cue was valid but not the nonspatial word cue (10%), (b) the nonspatial word cue was valid but not the location cue (10%), or (c) neither was valid (10%). Thus, if, for example, the Dutch words for “red on 12” (“rood op 12”) were presented, observers knew with a 70% probability that a color singleton would be presented at the top (12 o'clock) of the screen. Each participant performed 120 practice and 1,200 experimental trials. All conditions were randomized within blocks.

## Results

Table 6 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  for spatial and nonspatial cueing conditions. An ANOVA on  $A'$  with type of singleton, location cue validity, and nonspatial word cue validity as main factors only showed an effect of location cue validity,  $F(1, 15) = 6.455$ ,  $MSE = .014$ ,  $p < .05$ . As is clear from Figure 2, participants performed better when the location cue was valid (.90) than when it was invalid (.85). It is important to note that nonspatial word cue validity had no effect ( $F < 1$ ), nor did it interact with any of the other variables (all  $F$ 's  $< 2.471$ ). The absence of an interaction suggests that the nonspatial cue did not add anything above and beyond the spatial cue.

## Discussion

Experiment 6 showed that when spatial and nonspatial information is simultaneously available, only spatial information can be used to improve perceptual sensitivity. In line with Experiments 1 to 5, Experiment 6 showed that spatial information is highly efficient in improving the detection of signals whereas nonspatial information cannot be used to improve the gain for input.

## Experiment 7

Whereas symbolic spatial cues, such as arrows, were effective in guiding attention, one could argue that word cues indicating the

Table 6

*Results of Experiment 6 With Mean Percentage Hits, Mean Percentage False Alarms, Mean  $A'$  for Spatial and Nonspatial Cueing Conditions, by Cue Validity*

| Variable         | Nonspatial cue invalid |             | Nonspatial cue valid |             |
|------------------|------------------------|-------------|----------------------|-------------|
|                  | Invalid cue            | Valid cue   | Invalid cue          | Valid cue   |
| Hits (%)         | 74.7 (15.4)            | 83.5 (7.7)  | 77.8 (11.2)          | 84.1 (6.0)  |
| False Alarms (%) | 21.9 (21.5)            | 14.8 (20.9) | 21.9 (18.4)          | 18.5 (16.8) |
| $A'$             | 0.84 (0.12)            | 0.91 (0.04) | 0.86 (0.06)          | 0.90 (0.01) |

Note. Standard deviations are shown in parentheses.

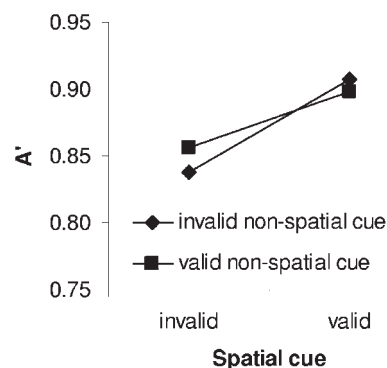


Figure 2. Experiment 6:  $A'$  for invalid and valid cueing when the cue provides spatial or nonspatial information about the upcoming target.

dimension (e.g., “color”) or the specific feature (e.g., “red”) to search for were not an adequate way to induce top-down guidance (see Theeuwes et al., 2006, for a similar argument). To test this notion in Experiment 7, instead of presenting a word cue, we presented as a cue the actual target singleton before the presentation of the search display. Instead of preparing to make a selection on the basis of a verbal cue, such as the word “color” or “red,” participants could now prepare for the actual target singleton. If the word cue is too abstract to induce a top-down set for target selection, we expected presenting the actual target singleton as a cue should induce a validity effect on  $A'$ .

## Method

**Participants.** Ten students who had not participated in the previous experiments (7 men and 3 women; mean age = 21.1 years, ranging from 18 to 25 years) participated in the experiment as paid volunteers.

**Design, stimuli, and procedure.** The experiment was exactly the same as Experiments 2 and 3 except that the actual target singleton was presented as a cue instead of a word cue (“color” or “shape”). This cue was exactly the same as the target singleton and consisted of a single red circle (color condition) or single green diamond (shape condition) presented at the centre of the display.

## Results

The data were analyzed in the same way as in the previous experiments. Table 7 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  as a function of target singleton and cue validity.

There was no significant main effect of target singleton,  $F < 1$ . There was a highly significant main effect of cue validity,  $F(1, 9) = 11.434$ ,  $MSE = .008$ ,  $p < .01$ . This indicates that participants performed better when the cue was valid (.88) than when it was invalid (.78). The interaction between target singleton and cue validity was marginally significant,  $F(1, 9) = 5.019$ ,  $MSE = .003$ ,  $p = .052$ , suggesting that color cueing was more efficient than shape cueing.

## Discussion

The experiment showed a clear cueing effect on target detectability. In other words, showing the actual target singleton before

Table 7  
Results of Experiment 7 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean  $A'$  as a Function of Target Singleton and Cue Validity

| Variable         | Color target singleton |             | Shape target singleton |             |
|------------------|------------------------|-------------|------------------------|-------------|
|                  | Invalid cue            | Valid cue   | Invalid cue            | Valid cue   |
| Hits (%)         | 68.3 (17.0)            | 88.2 (3.8)  | 74.3 (14.9)            | 83.5 (8.8)  |
| False Alarms (%) | 30.7 (12.6)            | 21.3 (8.0)  | 33.3 (21.0)            | 28.8 (8.7)  |
| $A'$             | 0.77 (0.09)            | 0.90 (0.01) | 0.79 (0.10)            | 0.85 (0.05) |

Note. Standard deviations are shown in parentheses.

the search display increases sensitivity in detecting the singleton. Even though the word cue could not affect the visual selection, presenting the actual singleton did affect perceptual selectivity. The present results are important because they indicate that nonspatial features can affect perceptual selectivity. However, a crucial question that needs to be answered is whether this cueing effect is genuinely endogenous (top-down) or exogenous (bottom-up).

### Experiment 8

Experiment 8 tested whether the cueing effect observed in Experiment 7 was the result of endogenous or exogenous cueing. As noted, in the exogenous version of location cueing, the cue has no predictive value regarding the location of the upcoming target (e.g., Jonides, 1981). When cueing effects are found when the location cue has no predictive value, this result is typically considered to be evidence that cueing is exogenous (bottom-up) and automatic (Jonides, 1981; LaBerge, 1981; Yantis & Jonides, 1990). Indeed, similar arguments were raised by Yantis and Egeth (1999) in the context of attentional capture. Yantis and Egeth argued that in order to determine whether particular effects are bottom-up, "It is necessary to observe the attentional effects of the attribute in question under conditions in which that attribute is explicitly task irrelevant, so that there is no incentive for the observer to attend to it deliberately" (p. 662-663). We applied the same reasoning to nonspatial cueing. We ensured that there was no reason to deliberately attend to the cue. Instead of presenting the cue with 80% validity, we presented it with 50% validity. In other words, the centrally presented cue had no predictive value with respect to the upcoming target singleton. As with location cueing, finding a cueing effect under these circumstances would indicate that nonspatial cueing by means of a centrally presented cue is bottom-up and automatic.

### Method

**Participants.** Eleven students who had not participated in the previous experiments (10 women and 1 man; mean age = 19.4 years, ranging from 17 to 23 years) participated in the experiment as paid volunteers. Data from one participant was excluded from further analysis because that participant's overall accuracy, mean percentage hits and mean percentage correct rejections, was less than 60% (57%).

**Design, stimuli, and procedure.** The experiment was the same as Experiment 7 except that instead of 80% validity the cue only had 50% validity. Participants performed 48 practice trials and 240 experimental trials. The presentation time of the cue was 500 ms. The time between the cue and the search display was 300 ms.

### Results

Table 8 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  as a function of target singleton and cue validity.

There was a significant main effect of target singleton, indicating that participants performed better when the target singleton was a color singleton (0.92) than when the target singleton was a shape singleton (0.77),  $F(1, 9) = 21.811$ ,  $MSE = .011$ ,  $p = .001$ . Furthermore, there was a main effect of cue validity,  $F(1, 9) = 13.817$ ,  $MSE = .001$ ,  $p < .01$ , indicating that participants performed better when the cue was valid (0.86) than when it was invalid (0.83).

### Discussion

Even though the cue had no predictive value, when it happened to be valid, it resulted in an increased sensitivity at the location of the target singleton relative to the invalid condition. Note however that the size of the validity effect in Experiment 7 with 80% validity was much larger than the validity effect in the current experiment in which cue validity was only 50%. This finding is confirmed by a between-experiments comparison showing a reliable interaction between experiment and validity,  $F(1, 18) = 5.67$ ;  $p < .05$ . This finding suggests that top-down set played a role because the cue was more effective when participants knew it was more beneficial for task performance. Even though this is a top-down effect, it should be realized that this reduced cueing effect may have nothing to do with the actual cue effectiveness once the cue is processed but may instead be related to strategies used by some observers on some trials. Indeed, it is possible that in Experiment 8, in which the cue had a validity of only 50%, some participants on some trials did not, or did not fully, process the cue. For example, it is possible that participants directed attention or their eyes away from the cue during the cue interval. In trials in which the cue is not processed or not fully processed, it may not be surprising that the cue is less effective. Experiment 9 was designed to test this notion.

Table 8  
Results of Experiment 8 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean  $A'$  as a Function of Target Singleton and Cue Validity

| Variable         | Color target singleton |             | Shape target singleton |             |
|------------------|------------------------|-------------|------------------------|-------------|
|                  | Invalid cue            | Valid cue   | Invalid cue            | Valid cue   |
| Hits (%)         | 88.1 (9.0)             | 93.6 (7.9)  | 68.3 (18.4)            | 72.8 (15.9) |
| False Alarms (%) | 20.0 (8.7)             | 16.7 (8.9)  | 31.9 (9.0)             | 31.9 (10.7) |
| $A'$             | 0.90 (0.05)            | 0.94 (0.05) | 0.75 (0.12)            | 0.78 (0.12) |

Note. Standard deviations are shown in parentheses.

### Experiment 9

Regardless of cue validity, the nonspatial cue showing the exact target singleton gave reliable cueing effects both in Experiments 7 and 8. However, as noticed, the cueing effect in Experiment 7, in which the cue had an 80% predictability, was much larger than in Experiment 8 in which it was nonpredictable (i.e., 50%). It is likely that in Experiment 8, in which the cue had only 50% predictability, participants did not put much effort into processing the cue. In Experiment 9 we tested this notion. We forced participants to process the cue and kept its validity at chance level (i.e., 50%). The experiment was exactly the same as Experiment 8 except that we inserted 20% catch trials in which the centrally presented cue had a small gap. If participants detected the gap in the cue, they had to indicate this by pressing a key. By introducing these catch trials, we ensured that participants processed the cue even though the cue did not predict the identity of the upcoming target singleton.

### Method

**Participants.** Eight students who had not participated in the previous experiments (7 women and 1 man; mean age = 19.6 years, ranging from 18 to 23 years) participated in the experiment as paid volunteers.

**Design, stimuli, and procedure.** The experiment was exactly the same as Experiment 8 except for the addition of 60 catch trials (20% of the trials). Catch trials were identical to experimental trials except that the central cue contained a small gap (0.4°) at one of four different positions. Participants made an unspeeded response by pressing the "1" key when they observed a gap in the cue. On catch trials, cue validity as well as target singleton was balanced and presented in random order.

### Results

Overall mean accuracy on catch trials was at 92.9% correct, indicating that participants followed the instructions and processed the cue. Table 9 presents mean percentage hits, mean percentage false alarms, and mean  $A'$  as a function of target singleton and cue validity.

For the  $A'$ , the analysis yielded a significant main effect of target singleton,  $F(1, 7) = 6.438$ ,  $MSE = .005$ ,  $p < .05$ , indicating that participants performed better when the target was a color singleton (.85) than when the target was a shape singleton (.78). More importantly, the main effect of cue validity was significant,  $F(1,$

7) = 9.094,  $MSE = .018$ ,  $p < .05$ , indicating that participants performed better when the cue was valid (.89) than when it was invalid (.75). Moreover, the two-way interaction between target singleton and cue validity failed to reach significance,  $F = 1$ .

### Discussion

In the present Experiment we introduced catch trials to ensure that participants processed the cue. As in Experiment 8, the centrally presented cue had no predictive value with respect to the upcoming target singleton (i.e., cue validity was 50%). As in Experiment 8 we found a reliable cueing effect. However, unlike Experiment 8, the size of this cueing effect is as large (a cueing effect of 0.14) as in Experiment 7 (a cueing effect of 0.10), in which the cue had a validity of 80%. Indeed, a between-experiments analysis indicates that the cueing difference between Experiment 7 and 9 was not reliable,  $F < 1$ .

Note that the size of cueing effect in Experiment 9 (0.14) was significantly larger than the cueing effect in Experiment 8 (0.03), as confirmed by a between-experiments comparison (Experiment 8 vs. Experiment 9,  $F(1, 16) = 7.282$ ,  $MSE = .004$ ,  $p = .01$ ). This suggests that when the cue is not predictive, participants may decide not to process the cue on all trials, making it less effective in generating cueing effects. As noted, even though this is a top-down effect, it should be realized that this reduced cueing effect has nothing to do with the actual cue effectiveness. Indeed, when participants are forced to process the cue even though it has no predictive value, the cueing effects are just as large as when it does predict the upcoming target singleton.

Overall, these findings indicate that regardless of its validity, the cue generates the same size cueing benefits as long as one ensures that participants process the cue. Because the cue effectiveness was not affected by its predictability, we can conclude that cueing with exact target singleton is exogenous in origin, not influenced by top-down set.

### General Discussion

The current findings show that top-down set for spatial information can affect perceptual sensitivity (Experiment 1). However, a top-down set for nonspatial information does not change perceptual sensitivity (Experiments 2, 3, 4, 5, and 6). So, knowing where the target singleton will appear affects perceptual selectivity; knowing what it is does not help selectivity. Furthermore, by presenting the object of search, perceptual sensitivity can be enhanced (Experiment 7). However, because this sensitivity effect is obtained even when there was no reason to attend to the cue, the effect should be considered to be bottom-up and automatic in nature (Experiments 8 and 9).

In line with recent suggestions by Prinzmetal et al. (2005), the experiments described here used a measure that is assumed to assess the effect of top-down set on the perceptual representation and not on processes that occur later in processing (see also Theeuwes et al., 2004, 2006). Previous studies that used RT as a dependent measure may have reported effects of nonspatial attention that may have nothing to do with initial visual selection but may represent effects that Prinzmetal et al. (2005) labeled "channel selection." Indeed, according to Prinzmetal et al., channel selection can formally be described as a decision process possibly related to

Table 9  
Results of Experiment 9 With Mean Percentage Hits, Mean Percentage False Alarms, and Mean  $A'$  as a Function of Target Singleton and Cue Validity

| Variable         | Color target singleton |             | Shape target singleton |             |
|------------------|------------------------|-------------|------------------------|-------------|
|                  | Invalid cue            | Valid cue   | Invalid cue            | Valid cue   |
| Hits (%)         | 68.8 (18.6)            | 92.0 (10.0) | 64.6 (23.0)            | 88.5 (5.4)  |
| False Alarms (%) | 28.8 (13.2)            | 15.3 (10.4) | 32.3 (19.4)            | 39.6 (19.9) |
| $A'$             | 0.77 (0.15)            | 0.93 (0.05) | 0.73 (0.18)            | 0.84 (0.06) |

Note. Standard deviations are shown in parentheses.



the selection of responses. Similarly, it is known that RT and signal detection measures index different aspects of attention-related processing (see, e.g., Hawkins et al., 1990; Handy et al., 1996). It is generally agreed that  $A'$  reflects earlier perceptual processing, such as the sensory encoding of a stimulus (see, e.g., Handy et al., 1996), whereas RT can reflect both earlier perceptual and later response-related operations.

The current findings have important implications for models of visual selection. Even though intuitively it appears to be plausible that knowing what you are looking for affects perceptual selectivity, the current findings show that top-down set for nonspatial features has no effect on selection. Even though previous studies have shown effects of top-down set for nonspatial features on RT (e.g., Müller et al., 2003; Treisman, 1988; Wolfe, 1994; Wolfe et al., 2003), the current study shows that the RT costs and benefits obtained in those studies may have had nothing to do with an improvement of the perceptual representation but may instead reflect effects on later (response) decision processes (e.g., Prinzmetal et al., 2005; Mortier et al., 2005).

Our finding that presenting the target singleton of search as a cue (Experiments 7, 8, and 9) has an effect on perceptual sensitivity indicates that nonspatial features are able to affect perceptual selection. The fact that this effect occurs regardless of the cue validity suggests that the effect is automatic and bottom-up. Even though the object of search was presented as a cue in the current paradigm, these effects are likely to be the same as the intertrial priming effects that have been reported in earlier studies. For example, Maljkovic and Nakayama (1994) investigated a mechanism they referred to as "priming of pop-out." Participants in the Maljkovic and Nakayama experiment searched for a feature singleton that was defined in either of two different ways: a red target among green distractors or a green target among red distractors. They showed that even when repetition of the feature value was at chance level (i.e., repetition was no more likely than alternation), repeating a target (but not the response) improved performance. In line with the current study, Maljkovic and Nakayama concluded that this effect is due to automatic (visual) priming that is basically not affected by top-down set (see also Pinto, Olivers & Theeuwes, 2005). Kristjansson, Wang, and Nakayama (2002) reported similar results and reported intertrial priming effects in conjunctive visual search. In their experiments, the identity of the potential target varied predictably from trial to trial. When the target to be found was the same for a few trials in a row, search performance became similar to that when the potential target was the same on all trials (see also Pinto et al., 2005, for a similar finding in pop-out search). These results provide strong evidence for intertrial priming. Kristjansson et al. (2002) argued that knowing all the target features on a given trial does not facilitate conjunction search. More importantly they claimed that, in addition to priming, there are no benefits for top-down guidance. They concluded that "the role of priming in visual search is underestimated in current theories of visual search and that differences in search times often attributed to top-down guidance may instead reflect the benefits of priming" (Kristjansson et al., 2002, p. 37). Moreover, similar priming effects were reported by Bravo and Nakayama (1992). In their study, the color of the upcoming target was predictable with consistent mapping and unpredictable with variable mapping, and this foreknowledge of target color in the consistent mapping condition led to faster response times.

It should be noted that the increased sensitivity due to priming that we observed in our experiments (and in, e.g., Maljkovic and Nakayama, 1994; Kristjansson et al., 2002; Pinto et al., 2005) is unlike the more traditional response priming (e.g., Bertelson, 1965; Pashler & Baylis, 1991), in which the facilitation of performance is due to priming of the probable response. In those experiments, performance improves because priming allows the advanced preparation of the most likely response. However, in our experiments, the cue did not provide any information about the required response. Instead the cue provided information about particular properties of the to-be-searched-for target (e.g., its color, shape, or location), but not which response to give. The facilitation of performance (i.e., the increased sensitivity) that we observed in our location cueing experiments (Experiments 1 and 6) and experiments cueing the exact target object (Experiments 7, 8, and 9) is, therefore, related to the initial selection of the target.

The present findings are related to those reported by Soto, Humphreys, and Heinke (2006, see also Soto, Heinke, Humphreys, & Blanco, 2005). They used a pop-out search task in which participants had to search for a line segment embedded in a particular item (e.g., a red square) among three other items (e.g., a blue circle, green triangle, and a pink diamond). Before each trial, participants had to remember a particular shape with a particular color (e.g., a red square), then to search for a tilted line segment among upright distractor line segments and, finally, perform a memory test. The line segments of the search task were each placed inside a shape that could match the to-be-remembered item in shape, color, or both. Soto et al. (2006) found that search for the tilted line was speeded when it was placed inside a (partially) matching object, whereas it was slowed when one of the distractor lines was placed inside the matching object. They concluded that in pop-out search, the content of working memory guides attention in a top-down way to the item that matches the representation in memory. The authors concluded that even with a highly salient target, similar to those that we employed in the present experiments, there is top-down guidance by memory representations. The study of Soto et al. (2006) is important because it suggests that, in pop-out search, the early preattentive stage of processing is influenced in a top-down way by nonspatial features kept in memory.

On the face of it, the conclusions reached by Soto et al. (2006) are opposite to our conclusions. But, rather than assuming that these effects are the result of top-down guidance by memory representations, we assume that these effects are the result of bottom-up priming. Note that the pattern of results reported by Soto et al. (2006), which shows that the presentation of the actual shape or color of a singleton can speed up RT for a singleton, can very well be explained by bottom-up priming. There may be no need to actually keep the item in memory to obtain the very same results. In fact, the experimental procedure used by Soto et al. (2006) makes it quite likely that priming played a role. Unlike our experiments, in which the cue was presented for 850 ms followed by an interstimulus interval of 700 ms, in Soto et al. (2006), the cue (i.e., the to-be-memorized item) was presented for only 129 ms followed by an interstimulus interval of 188 ms, leaving observers relatively little time to encode and consolidate the item into memory before they needed to start searching for the target. The very short time intervals employed by Soto et al. (2006) are typically used in priming studies and are considered to represent automatic

processing of prime and target rather than effortful top-down processing. For example, in the classic letter priming task of Posner and Snyder (1975), it was shown that it takes about 300 ms before central (top-down) mechanisms can have an effect. Therefore, it seems likely that the effects in the Soto et al. (2006) study (which are similar to the effect that we report in Experiments 7, 8, and 9) are not due to top-down guidance but merely reflect bottom-up priming. Arguments that their findings cannot be due to bottom-up priming are not provided by Soto et al. (2006), other than by reference to a previous study that explicitly tested this assertion. Indeed, in this previous study, which used a search task in which the target did not pop-out from the background, Soto et al. (2005) showed effects of the memorized cue on the fastest RTs and on the first saccade. In a control experiment (their Experiment 4), they showed that their findings were not the result of automatic priming but that the cue had to be remembered in order to get the effect. Even though it is feasible that priming did not play a role in Soto et al.'s 2005 study, which involved relatively slow search, it is possible that the currently used fast pop-out search tasks are more sensitive to reveal effects of priming. For example, in slower search tasks, initial priming could decay too rapidly to affect search. Indeed, by the time the serial attentional focus reaches the item that was primed, so much processing has taken place during scanning of the display that the priming effect has worn off.

As noted, previous studies have shown effects that suggest that top-down set for nonspatial information can affect perceptual selectivity in pop-out search (e.g., Müller et al., 2003; Treisman, 1988; Wolfe et al. 2003). For example, in one of the experiments of Müller et al., participants received a verbal cue indicating the dimension of the upcoming target singleton (i.e., the words *color* or *shape*), a procedure similar to the one we employed in our Experiment 2. Instead of participants responding to the line segment inside the color or shape singleton, as in our current study, Müller et al. participants had to make a speeded response and decide whether a color or shape singleton was present in the display. Müller et al. showed nonspatial cueing effects indicating that knowing the dimension of the upcoming target singleton affected the speed of responding. For example, when the color dimension was cued, participants were faster in deciding that a color singleton was present than they were when a shape singleton was present. Even though, on the face of them, these findings seem to suggest that nonspatial information can affect the efficiency of visual selection, it should be realized that in the Müller et al. study the cue may not only have affected visual selection; it may also have affected response selection because the cue provided information about the target participants needed to respond to (see Mortier et al., 2005; Prinzmetal et al., 2005, for a similar arguments). Indeed it is possible that RT costs and benefits obtained in previous studies, such as those by Müller et al., may have nothing to do with an improvement of the perceptual representation but may instead reflect effects on later (response) decision processes (e.g., Cohen & Magen, 1999; Theeuwes et al., 2006).

In the current study, the cue only provided information about properties of the singleton to search for (its shape, color, location) and never provided any information about the response. In addition, we employed measures derived from SDT that are assumed to reflect early perceptual processes (e.g., Hawkins et al., 1990; Handy et al., 1999). Therefore, finding cueing effects of spatial cueing (Experiments 1 and 6) and cueing effects due to priming

(Experiments 7, 8, and 9) can only be attributed to initial visual selection.

Our current notion suggests that nonspatial feature information cannot modulate early perceptual selectivity in a top-down manner. In line with the classic two-stage approach of visual selection (e.g., Broadbent, 1958; Neisser, 1967; Treisman and Gelade, 1980), this suggests that the early preattentive parallel stage of processing cannot be influenced in a top-down way by nonspatial feature information. In terms of modern conceptions, this finding suggests that the initial flow of information through the brain cannot be modulated in a top-down way by nonspatial information. It is assumed that during the first feedforward sweep of information through the brain, saliency information is extracted from the visual scene and is represented in our visual system as a saliency map (e.g., Itti & Koch, 2000, 2001; Nothdurft, 2002; Parkhurst, Law, & Niebur, 2002). Our viewpoint is that after the initial feedforward sweep of information through the brain, the initial bottom-up information may be modified by recurrent processing (also referred to as reentrance processing; cf. Di Lollo, Enns, & Rensink, 2000). Information flows through various horizontal connections within and between areas and feedback connections from higher areas back to lower ones. Our notion is that the modifications of the initial bottom-up saliency map through recurrent processing is the way top-down control is implemented in the brain. Thus, the reentrance signals deriving from various parts of the brain modulate the neural activity within the saliency map to fit the current goals of an observer (e.g., Kastner & Ungerleider, 2000). Thus, initial bottom-up driven selection may become more and more goal driven as more reentrance signals arrive at the saliency map.

The notion that early visual selection can only be affected by spatial information and that nonspatial information can only have an effect at later stages of processing is consistent with several electrophysiological studies. Indeed, event-related potential (ERP) studies have shown early sensory-specific ERP components (P1 and N1) elicited over posterior visual cortical areas in response to visual stimuli at attended compared to unattended locations (e.g., Eimer, 1995; Hillyard & Münte, 1984; Mangun, 1995). Amplitude modulations in response to spatial cues start as early as 80 ms after stimulus onset. In contrast, when attending to nonspatial features, such as color or shape, there is an enhanced sustained negativity that starts much later, at about 150 ms poststimulus (e.g., Eimer, 1995; Heslenfeld, Kenemans, Kok, & Molenaar, 1997). Consistent with our findings showing an increased sensitivity in response to spatial information, ERPs in response to spatial cueing show a selective amplification of attended inputs within the visual-cortical pathways as early as 80 ms. In response to cueing of nonspatial features, such as color or shape, such early sensory gain control has never been reported.

ERP studies suggest that, with respect to spatial attention, the cortical mechanisms involved consist of interconnected dorsolateral prefrontal and posterior parietal cortical areas. These areas can modulate incoming visual information via projections to both dorsal and ventral extrastriate visual pathways (Martinez et al., 1999). It is clear from ERP studies that selection on the basis of nonspatial information is characterized by a completely different ERP pattern, indicating that the cortical mechanisms involved in nonspatial selection are qualitatively different from those involved in the selection on the basis of space.

The current study shows that top-down knowledge regarding the location of the upcoming targets has an effect on perceptual sensitivity. In line with the above conception, this implies that top-down control for location information operates on the saliency map. Thus, one has to assume that during the cue interval, recurrent top-down processing (e.g., dorsal frontoparietal activation; see Corbetta & Shulman, 2002) may change the neural activity in the saliency map. In this view, top-down knowledge regarding location information affects the neural activity in the saliency map before the first feedforward sweep of information goes through the brain. This indicates that before an image hits the retina, before any information runs through the brain, top-down signals have changed the neural activity in the saliency map. For example, directing spatial attention to the left side of the visual field increased stimulus-evoked activity in extrastriate visual areas of the right hemisphere, whereas directing attention to the right side of the visual field increased activity in extrastriate visual areas of the left hemisphere (Heinze et al., 1994; Vandenberghe et al., 1997). The early selective enhancement (i.e., improved initial sensory gain) on the basis of spatial information is carried out by extrastriate visual areas such as V3-V4. These amplified signals are conveyed back to V1 by feedback projection, which changes the saliency signal of the attended signal (e.g., Lamme & Roelfsema, 2000).

Our findings suggest that top-down control for nonspatial information cannot modulate the initial sweep of information. This implies that when nonspatial information is provided (e.g., the target is red), the first feedforward sweep is bottom-up and not biased by top-down information. The saliency map encodes the saliency of objects in their visual environment. Neurons in this map compete among each other, giving rise to a single winning location (cf. winner take all) that contains the most salient element. In line with the classic two-process theories of attention (e.g., Broadbent, 1958), the saliency map is the result of preattentive parallel encoding across the visual field calculating differences in simple visual features, such as intensity, contrast, color, and orientation (Itti & Koch, 2001; Koch & Ullman, 1985). In the first feedforward sweep, attention is captured in a bottom-up fashion to the most salient location. Only after the first sweep, top-down control may allow a fast disengagement of attention.

The current findings are consistent with studies investigating attentional capture. Theeuwes (1991, 1992, 1994) showed that knowing that you have to search for a shape singleton cannot prevent attentional capture by a completely irrelevant color singleton, not even after 2,000 trials of practice (see Theeuwes, 1992, Experiment 2). In addition, there is evidence that, after the initial sweep of information, recurrent processing involving top-down control may allow immediate disengagement of attention and redirect it to objects that are in line with the top-down goals. Indeed, Theeuwes, Atchley, & Kramer (2000) showed that bottom-up capture of attention is short lived and that, after attention has been captured by the most salient singleton, it can be redirected within 100 ms after stimulus presentation (see also, Theeuwes, 1994).

Along similar lines, van Zoest, Donk, & Theeuwes (2004) recently showed that fast eye movements are completely driven by bottom-up salience signals whereas slow eye movements are controlled in a top-down way. Note that the current findings are inconsistent with the contingent-capture hypothesis of Folk et al.

(1992). If selection would be under top-down control, as Folk et al. (1992) assume, then one would have expected that nonspatial cueing would be just as effective as spatial cueing. It is clear that this is not the case. However, the priming effects of Experiments 7, 8, and 9 could be related to the contingent-capture hypothesis in the sense that these selection effects may reflect effects that are contingent on some top-down control setting. Note however, unlike contingent capture, this bottom-up selection is not dependent on the adoption of some attentional set but merely the result of processing the cue. Processing the cue will result in bottom-up selection benefits regardless of whether the cue is predictive or not.

In sum, top-down set for spatial information is qualitatively different than top-down set for nonspatial information. Our findings suggest that spatial information is indeed "special" (Tsal & Lavie, 1988), suggesting that top-down expectancy with respect to the location of the upcoming target can modulate neural activity. Even though some fMRI studies have shown that top-down expectancy for nonspatial features may alter neural modulation (e.g., Wojciulik & Kanwisher, 1999; Giesbrecht, Woldorff, Song, & Mangun, 2003), the current findings suggest that this neural modulation does not necessarily influence initial perceptual selection. Indeed, as argued by Martinez and Hillyard (2005), it is possible that the nonspatial attentional effects observed with fMRI represent a top-down bias producing a sustained attention-related activity without necessarily modulating the initial stimulus-evoked response.

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## Appendix A

*d'* Values for All Experiments by Cue Validity

| Experiment | Color target singleton |             | Shape target singleton |             |
|------------|------------------------|-------------|------------------------|-------------|
|            | Invalid cue            | Valid cue   | Invalid cue            | Valid cue   |
| 1          | 1.20 (0.63)            | 2.18 (0.24) | 0.85 (0.69)            | 2.01 (0.27) |
| 2          | 1.49 (0.57)            | 1.88 (0.29) | 1.40 (0.58)            | 1.41 (0.49) |
| 3          | 2.43 (0.56)            | 2.79 (0.33) | 1.35 (0.77)            | 1.41 (0.73) |
| 4          | 1.51 (0.72)            | 1.95 (0.27) | 1.18 (1.63)            | 1.44 (0.64) |
| 5          | 2.02 (0.23)            | 1.85 (0.17) |                        |             |
| 7          | 1.06 (0.52)            | 2.02 (0.12) | 1.26 (0.68)            | 1.63 (0.48) |
| 8          | 2.17 (0.64)            | 2.74 (0.67) | 0.99 (0.54)            | 1.21 (0.81) |
| 9          | 1.18 (0.82)            | 2.71 (0.75) | 0.97 (0.83)            | 1.58 (0.59) |

|   | Nonspatial cue invalid |             | Nonspatial cue valid |             |
|---|------------------------|-------------|----------------------|-------------|
|   | Spatial cue            |             | Spatial cue          |             |
|   | Invalid                | Valid       | Invalid              | Valid       |
| 6 | 1.62 (0.66)            | 2.08 (0.46) | 1.63 (0.49)          | 1.95 (0.18) |

*Note.* Standard deviations are shown in parentheses.

Received August 18, 2006

Revision received March 10, 2007

Accepted March 10, 2007 ■

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